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Measurements and analysis of cavitation in a pressure reducing valve during operation – a case study

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Abstract

This paper proposes a methodology and presents its practical application for evaluating whether a pressure reducing valve (PRV) is under cavitation during its operation in a water distribution system. The approach is based on collecting measurements over a 24-hour period such that high demand and low demand times are included. The collected measurements allow evaluation of four indicators related to cavitation, namely the hydraulic cavitation index, noise generated by the valve, acoustic cavitation index and the spectra of the noise. These four indicators provide sufficient information for diagnosis of cavitation with high certainty.

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Keywords:

pressure reducing valve (PRV), cavitation, hydraulic measurements, acoustic measurements

1. Introduction

Cavitation is a phenomenon related to formation of vapour bubbles inside liquids, in our case water, under conditions where local liquid pressure falls below the vapour pressure under given temperature. If these newly formed bubbles are subsequently subjected to high pressure they ultimately collapse generating pressure shock waves. In case of a plunger valve depicted in Figure 1 cavitation may occur in the narrowing section of the valve between the plunger and its body. If the water velocity is sufficiently high, due to either high flow or small valve opening, the pressure can drop below the water vapour pressure of the water in accordance with the Bernoulli principle. These vapour bubbles are then carried by the liquid downstream where the pressure ultimately recovers to its normal value causing the bubbles to implode and produce high pressure waves. If the bubbles implode in the vicinity of the internal valve surface they are likely to cause damage to the valve wall. The valves should therefore be sized in such a way that the pressure operating points are always above a hydraulic cavitation curve - see Figure 3. In practice, this task may sometimes be difficult to achieve as the operational conditions may change in time due to changes in valve flows and, as a result, the valve can operate under cavitation that may lead to more or less extensive damage. Cavitation damage can be checked by inspecting the valve and downstream pipework, however this may prove to be a costly op-

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eration as it requires taking the valve off-line. There is therefore a clear need for a non-invasive method to assess the valve's operating conditions with respect to cavitation during normal valve operation. However, the level of cavitation is notoriously difficult to assess and a single indicator may not be sufficient to assess the extent of cavitation in the system or conclude with certainty that cavitation is not taking place. For this reason the method proposed in this paper is based on many indicators involving both hydraulic and acoustic variables.



Fig. 1: Cross-section of the VAG plunger valve.

All relevant measurements were collected over a 24-hour period to ascertain that information from high demand (day) and low demand (night) times is included in the data [1]. The experimental set-up was designed to take the measurements of hydraulic variables such as valve inlet and outlet pressures and valve flow, as well as acoustic variables obtained from four acoustic sensors. An accelerometer was placed on the upstream pipe, the valve, and the downstream pipe. Additionally a capacitor microphone was positioned in the air close to the valve. The acoustic sensors were connected to sound recording equipment which measures both the signal level (in dB) and the sound frequency spectra. The collected measurements allowed evaluation of a number of indicators related to cavitation such as the cavitation index σ_{ISA} [2], the noise generated by the valve as a function of valve position, the noise level against the sigma coefficient (acoustic cavitation characteristic), and the frequency spectra of the signals from acoustic sensors at different times. These four indicators were then compared one against another to facilitate the diagnosis of cavitation with high certainty. The experiment is not invasive and comparatively cheap to run. Once the equipment is installed, data collection can be done automatically within a 24 hour period. This paper presents details of the case-study which confirmed the validity of the approach. The paper is organised as follows: Section 2 explains the measurement set-up while Sections 3 to 6 describe and evaluate the respective cavitation indicators. In Section 3 the cavitation coefficient σ_{ISA} is compared against the cavitation curve provided by the valve manufacturer VAG. In Section 4 the measured noise level is compared with the manufacturer noise curve. Section 5 investigates the acoustic cavitation characteristic and, finally, Section 6 analyses the frequency spectra of the signals measured by three accelerometers.

2. Method and measurement setup

The method is illustrated by application to a specific case study with the schematic and position of sensors depicted in Figure 2. Three accelerometers were placed in the rig: first on the upstream pipe, second on the valve and third

on the downstream pipe. Additionally, a capacitor microphone which measures sound pressure level in the air was attached to one of the four PRV loop handles - see Figure 1. All four sensors were connected, using electronically balanced lines to avoid electrical interference on the recorded signals, to sound recording equipment, which in turn was connected to a laptop. The capacitor microphone was calibrated in dB SPL (sound pressure level), while the accelerometers were not calibrated. Readings of the four signals were recorded at 48 kHz sampling rate and with a 24-bit resolution, where the maximum corresponds to 0 dBfs (decibel full scale). The equipment used for audio recording consisted of following items:

- DPA 4060bm. Omnidirectional 1/8" capacitor microphone (www.dpamicrophones.com)
- C-DUCER CPM 1/8 and 2/8. 8" contact microphones (www.c-ducer.com)
- MOTU Traveler. Microphone preamplifier, AD-DA converter and audio interface (www.motu.com)
- Logic Studio. Digital audio workstation (www.apple.com)

The PRV inlet and outlet pressures as well as flow rate were recorded by the existing telemetry system at 15 minute intervals and were provided in a spreadsheet file. The sound was recorded continuously over 24-hour period. The site was visited periodically to verify if the equipment was working correctly and back up the recorded data.

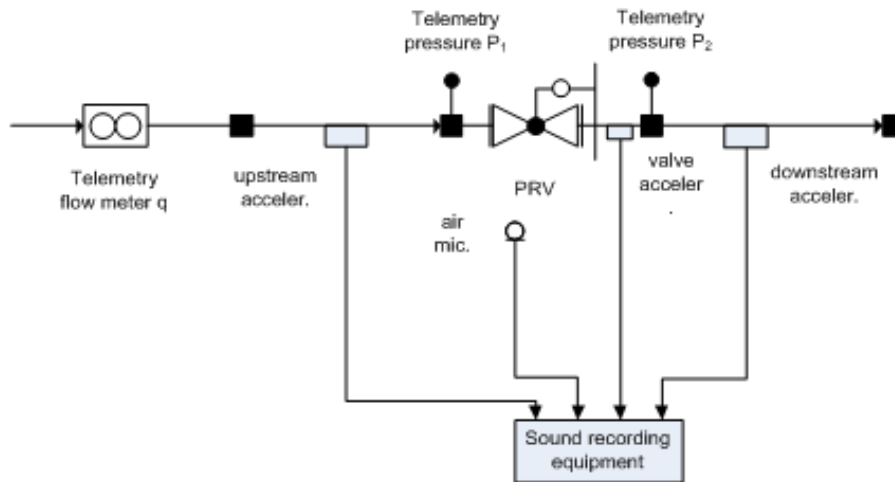


Fig. 2: Experimental setup for measuring cavitation in a VAG pressure reducing valve (PRV).

3. Analysis of the hydraulic measurements

The following hydraulic variables were measured: inlet valve pressure P_1 , outlet valve pressure P_2 , and valve flow rate Q . P_1 and P_2 were then used to calculate the sigma cavitation coefficient σ_{ISA} defined in Equation 1.

$$\sigma_{ISA} = \frac{P_1 - P_V}{P_1 - P_2} \quad (1)$$

where P_V denotes vapour pressure of water at a given temperature.

The value of σ_{ISA} depends on valve position. The valve manufacturer normally provides a cavitation curve, i.e. an experimentally derived relationship between σ_{ISA} and valve opening which constitutes the border line between cavitation area (below the curve) and no-cavitation area (above the curve). The cavitation curve for the VAG valve is plotted in Figure 3 together with the operating points measured by the authors on the experimental rig.

The measurements in Figure 3 represent 96 samples collected at 15 min intervals over the 24 hour period. The valve position was being automatically adjusted by a controller manipulating the valve opening in response to changes in demand and varied between 40% and 73%. The control objective of this PID controller was to maintain constant valve

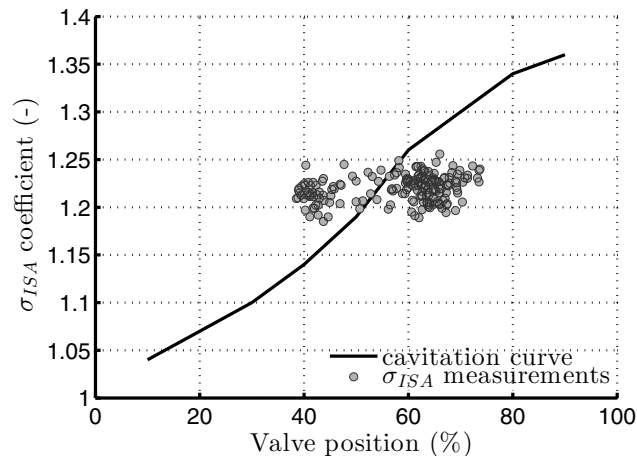


Fig. 3: Measured sigma coefficients against valve opening during valve operation and the VAG valve cavitation curve.

outlet pressure irrespectively of the upstream pressure and demand. Figure 3 shows that that the operating points for small valve openings, i.e. below 55%, are above the cavitation curve while for large valve openings, i.e. above 55%, the operating points fall below the cavitation curve. This observation suggests that in the examined PRV cavitation occurs only at large valve openings, above 55%, as a result of high flow and hence high water velocities and hence low dynamic pressures.

4. Analysis of the valve noise

Normally, manufacturers also provide noise characteristics of their valves, i.e. the measured/expected noise level against valve opening. For the VAG valve under consideration the valve noise characteristic is presented in Figure 4 together with the noise measurements obtained in our experimental rig. It is worth pointing out that noise emission considered by the manufacturer represents noise produced by the valve valve only and does not take into account the additional noise produce by adjoined structures such as pipes [1].

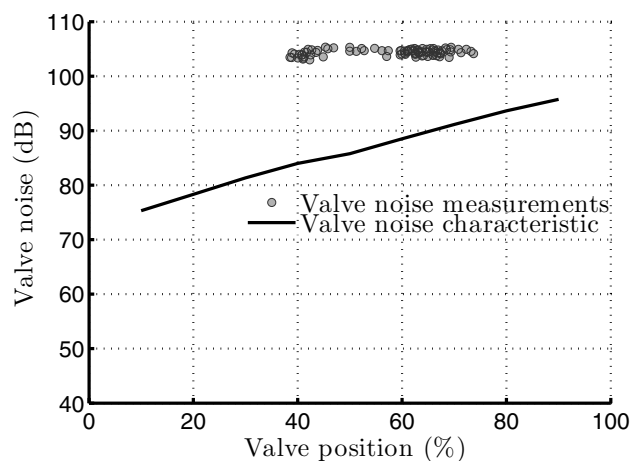


Fig. 4: Valve noise measurements against valve opening and the VAG valve noise characteristic.

The valve characteristic represents mainly turbulence noise resulting from rapid deceleration of the fluid that occurs as the flow area increases downstream of 'vena contracta'. Normally, the noise increases with valve opening and the resulting increase in flow, as depicted in Figure 4. This noise is generally below 100 dB. Apart from *turbulence noise* there are two other types of noise to consider when applied to cavitating systems: *cavitation noise* and *flashing noise*. *Cavitation noise* is produced by implosions of vapour bubbles returning to the liquid state in the cavitation process. Cavitation noise may be described as rattling sound and its level can exceed 100 dB. *Flashing noise* occurs when a portion of the fluid vaporises without the subsequent bubble collapse. The noise results from deceleration and expansion of the two-phase flow stream. Generally, flashing noise is lower than the cavitation noise. From the measurements taken over a 24-hour period and shown in Figure 4 we can deduce that the level of noise emitted by the valve falls between 103 dB and 105.5 dB SPL and remains nearly constant for valve openings between 40% and 75%. The noise measurements suggest that the major contributors to noise are cavitation and flashing, not the turbulence because the recorded noise does not depend on valve position. Since the noise from turbulent flow should, in theory, increase with valve opening and thus, flow, but instead it remains constant, the source of this noise, through elimination, can either be flashing and/or cavitation.

5. Analysis of the acoustic cavitation characteristic

The aim of this section is to analyse the relationship between the cavitation coefficient σ_{ISA} calculated according to Equation 1 and the acceleration/noise level recorded by the accelerometer sensors. Figure 5 depicts a typical pattern [2,3] which includes three cavitation regimes: *incipient cavitation* where cavitation is just beginning to develop, *constant cavitation* and the *maximum vibration regime* where mixture of cavitation and flushing takes place. The characteristic feature of this regime is a positive slope of the acceleration versus sigma. The acceptable operating point in the *constant cavitation* regime, which doesn't cause damage to the valve, is marked in Figure 5 with a symbol σ_{mr} .

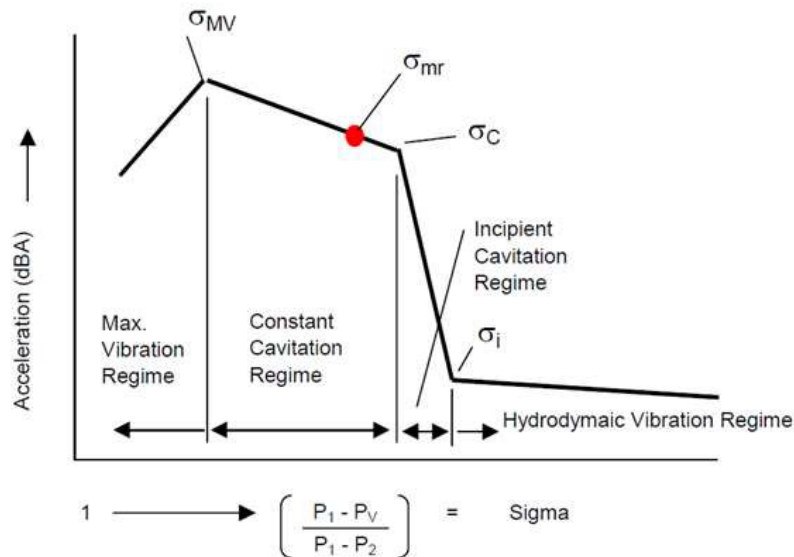


Fig. 5: A typical relationship between sigma and acceleration/noise in a control valve.

In our case the cavitation coefficient is quite small and covers only a very narrow part of the characteristic due to the fact that it was measured during normal operating conditions. In order to deduce which regime the measured cavitation coefficient represents it is necessary to measure the slope of the accelerometer readings versus the σ coefficient and carry out a stringent statistical test of the measured slope. The statistical analysis was carried out using the Data Analysis tool in Excel. The results of the regression and the subsequent statistical analysis for the valve accelerometer

are displayed in Figure 6 and Table 1. The calculated trend line equation: $y = 30.614x - 66.649$ has a rather low associated R^2 coefficient of 0.516 due to wide scatter of the data. The slope of the line is positive and is consistent with the maximum vibration regime in Figure 5. Statistical analysis of the significance of the slope value is presented in Table 1. The results presented in Table 1 indicate that H_0 hypothesis (i.e. that the slope is zero) should be strongly rejected due to a very small F Significance value $5.261 \times 10^{-16} < 0.05$. It is also consistent with very small P-values for the intercept and the slope. Finally it is important to notice that the confidence interval at the 95% level for the slope [24.44 36.79] does not include 0.

Table 1: Results of the statistical analysis of the significance of the slope of the acceleration against sigma characteristic on the valve.

Parameter	Value	Std. error	t-stat	p-value	Lower 95%	Upper 95%	F	F Significance
slope	30.61	3.108	9.850	5.261E-31	24.44	36.79	97.02	5.261E-16
intercept	-66.65	3.794	-17.57	5.509E-31	-74.19	-59.11		

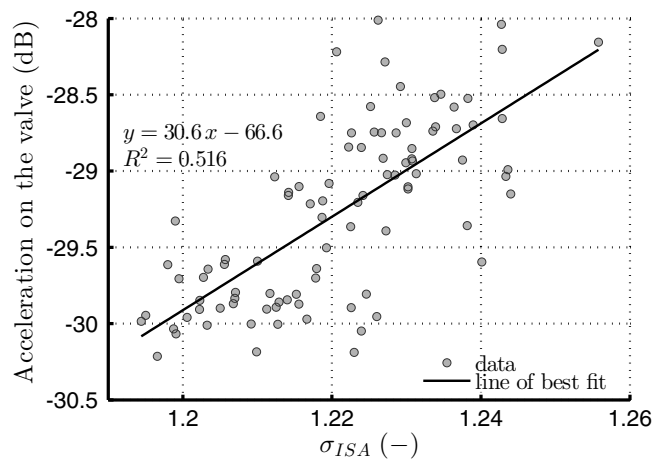


Fig. 6: Readings from the piezoelectric accelerometer on the valve against σ_{ISA} .

A similar test has been carried out for the calibrated signal from the capacitor microphone. The calculated trend line equation is $y = 19.3x + 80.8$, albeit with a rather low associated R^2 coefficient of 0.232. The regression results are listed in Table 2 and the regression line together with all data points are presented in Figure 7. The data in Table 2 show that the F Significance value is low ($9.954 \times 10^{-16} < 0.05$), albeit higher than for the valve accelerometer data (Table 1). The confidence interval for the slope is [12.02 26.66] and does not include 0. This represents strong evidence that the slope is positive and consistent with the maximum vibration regime illustrated in Figure 5 for which flashing and cavitation takes place.

Table 2: Results of the statistical analysis of the significance of the slope of the acceleration against sigma characteristic on the valve.

Parameter	Value	Std. error	t-stat	p-value	Lower 95%	Upper 95%	F	F Significance
slope	19.34	3.685	5.249	9.954E-07	12.02	26.66	27.55	9.954E-07
intercept	80.77	4.498	17.95	1.168E-31	71.83	89.70		

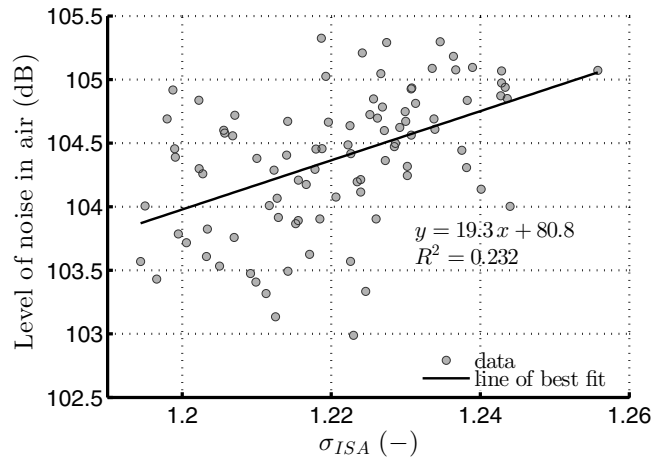


Fig. 7: Readings from the calibrated capacitor microphone positioned in the air vs. σ_{ISA} .

6. Analysis of the spectra of acceleration/noise measurements

This section analyses the frequency spectra of the signals recorded by the accelerometers and the microphone. The data are presented in two ways: the frequency spectra recorded by all four sensors at 10:00 am when σ_{ISA} happened to be large (see Figure 8) and the frequency spectra recorded on the valve and the downstream pipe at different times coinciding with both large and small σ_{ISA} values (see Figures 9 and 10 respectively). Since acoustic analysis of cavitation is not yet well developed and hence it is difficult to find trustworthy references, analysis of frequency spectra resulting from cavitation is not a straightforward process. As a starting point we can look at typical spectra from a cavitation experiment found for instance in Ceccio and Brennen[4]. Vibrations measured on the surface of a pipe or a valve result from the noise generated by the flow of liquid within the pipe structures but their properties, i.e. their amplitude vs. frequency characteristics are also strongly affected by the acoustic transmission properties of pipe and valve walls. A transmission characteristic of a pipe/valve has typically has an inverse V shape with strong attenuation of low and high frequencies and so pipes function similarly to a band pass filter [5]. Taking all this into consideration we will try to analyse the spectra recorded by different sensors and at different operating points as described further below.

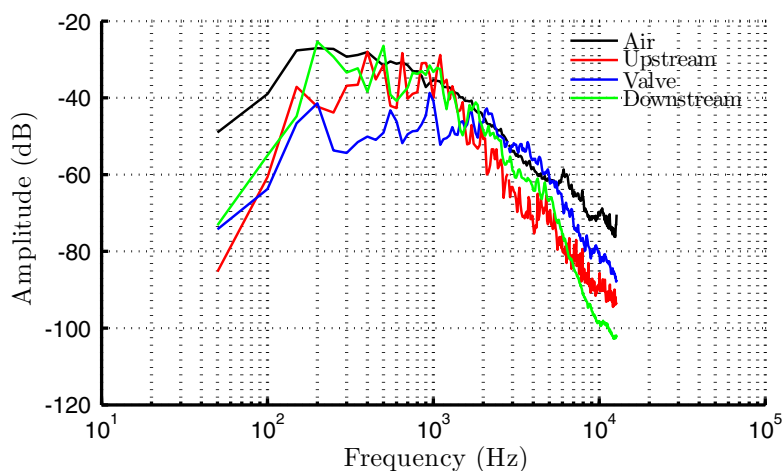


Fig. 8: Noise spectra from four sensors at 10:00 (large σ_{ISA} value).

The frequency spectra from the upstream pipe, the valve, and the downstream pipe are similar in shape but different in magnitudes (see Figure 8). Compared to the valve spectrum high frequencies on the upstream and downstream pipe are attenuated while attenuation on low frequencies is less clear. In the middle frequency range we seem to observe some signal amplification which might be due to resonance of the pipe/valve system. The signals are also strongly correlated. The correlation coefficient between the spectra from the upstream pipes and the valve is 0.935 while the correlation coefficient between the spectra recorded on the valve and on the downstream pipe equals 0.985. Such high correlation coefficients suggest that vibrations must be transmitted from one component to another through mechanical connections as well as through liquid flow. Since vibrations propagate from one part of the system to another and the signals are correlated, it is perhaps more informative to compare the spectra of each component separately, so that pipe/valve transmission properties are fixed and the differences between the spectra are caused by the changes in the flow regime only. The frequency spectra for the valve at different times are shown in Figure 9, while the spectra for the downstream pipe are displayed in Figure 10.

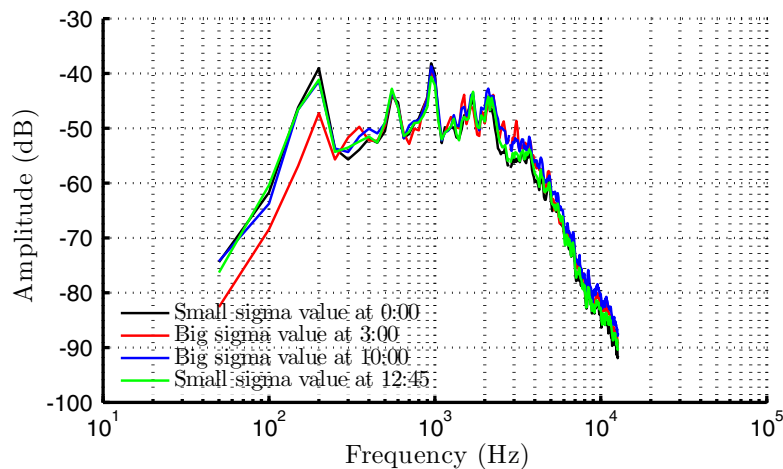


Fig. 9: Noise spectra from the valve at different times.

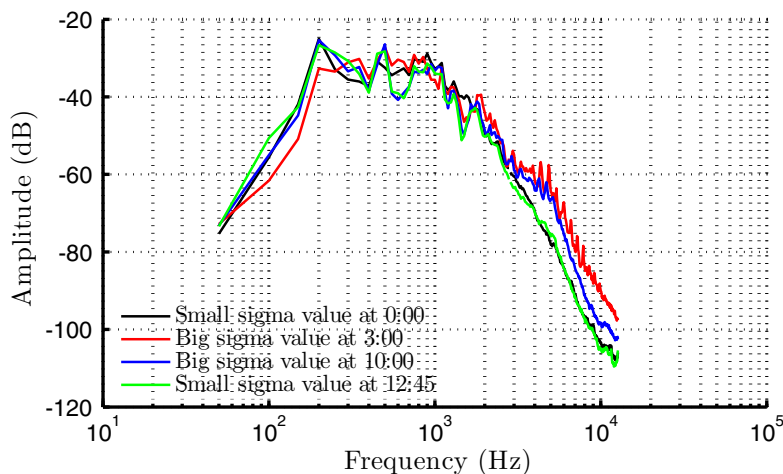


Fig. 10: Noise spectra from the downstream pipe at different times.

In both figures we can observe that for low frequencies vibrations recorded under operating conditions characterised with small σ values (at times 0:00 and 12:45) are stronger than for the the ones with large σ values - especially at 3:00 am. At 10:00 am this difference is less visible suggesting that low frequency noise is also flow dependent and hence it is likely to be caused not only by flushing (as later suggested) but also partly by turbulence, which itself increases with flow. The opposite is true in the high frequency range, i.e. that vibrations are stronger under conditions with higher σ values. This observation is consistent with the hypothesis that under small sigma values noise is created mainly due to flushing which generate low frequency noise as it is associated with production of big bubbles or no bubbles at all, while for large σ values noise production is caused mainly by cavitation generating high frequency noise from explosion of small bubbles. It is a general rule that small bubbles generate higher frequency noise than big bubbles [3]. It is especially evident in Figure 10 which presents the vibration frequency spectra recorded on the downstream pipe. It is visually apparent that in the high frequency range the red line, corresponding to recorded noise at 3:00 am coinciding with a large σ value, lies above all other spectra and exhibits prominent peaks characteristic of the presence of cavitation [4].

7. Conclusions

The proposed cavitation diagnostic method relies on the evaluation of four separate cavitation indicators obtained from a measurement experiment carried out over a 24-hour period during a normal operation of the analysed valve. The measured variables are: acceleration on the upstream pipe, acceleration on the valve, acceleration on the downstream pipe, and noise level in the air in the vicinity of the valve. The following observation were made in this particular case-study. Despite of the valve position varying quite significantly between 40% and 73%, the cavitation coefficient σ_{ISA} remained very small and varied in a narrow range between 1.194 and 1.256 as a result of a comparatively constant valve inlet pressure. Analysis of the telemetry data showed that at small valve positions below 55% the operating points, i.e. σ_{ISA} vs valve opening, lie above the cavitation curve pointing at lack of cavitation in the system. Under higher valve opening above 55% the operating points fall below the cavitation curve suggesting the presence of cavitation. However, the remaining three indicators analysed in this paper pointed to continuous presence of cavitation. According to the valve noise characteristic presented in Figure 5 noise should theoretically increase gradually between 84.77 dB for a 40% valve opening and 91.14 dB for 70% valve opening. In reality the noise level in the air was high, with low variability, an between 103.0 dB and 105.5 dB. The measurements were done in a highly reverberant room and not in an anechoic environment. It is therefore possible that other noises and deflected sound waves influenced the SPL measurement. Nevertheless, it is quite certain from our data that there was no significant difference in terms of SPL in the room between different times of the day suggesting that either the valve was cavitating at all times or that noise measurements in the air do not offer much information about hydraulic conditions inside our system. Statistical tests carried out in Section 5 indicated that the slopes of the acoustic characteristics, i.e. acceleration on the valve an noise level in the air vs. σ_{ISA} are both positive, although the noise in the air data is less informative. These findings correspond to the regime of maximum vibration illustrated in Figure 5 and suggest that the valve is exposed either to flashing or cavitation. Presence of cavitation in the system was also confirmed through analysis of the frequency spectra of the respective signals from the valve and the air. In high frequency range the spectra corresponding to operating points with large σ values are above the spectra corresponding to operating points with small σ values. If σ increases cavitation dominates over flushing while if σ decreases flashing plays the dominant role. All four indicators pointed to the presence of flushing/cavitation in the system. Subsequently the valve was inspected and the physical damage to the valve has been confirmed.

8. Acknowledgements

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